Some decay modes of the 1^{-+} hybrid meson in QCD sum rules revisited

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Abstract

The pionic coupling constants in the decays of the 1^{-+} hybrid meson are calculated. The double Borel transformation is invoked and continuum contribution is subtracted. The decay widths of the processes $1^{-+} \to \rho\pi, f_1\pi, \pi\gamma$ are around $40, 100, 0.3$ MeV respectively. Comparison is made with previous calculations using three point correlation functions.

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There appears increasing experimental evidence for a $J^{PC} = 1^{-+}$ hybrid meson. E852 [1] and Crystal Barrel [2] collaboration reported a resonance with mass and width $1370 \pm 16^{+50}_{-30}$MeV, $385 \pm 40^{+65}_{-105}$MeV and $1400 \pm 20 \pm 20$MeV, $310 \pm 50^{+50}_{-30}$MeV both in $\eta\pi$ channel respectively. Beladidze et al. in VES experiment at IHEP reported a broad signal in the $\eta\pi^-$ state [3]. Very recently E852 collaboration observed a $J^{PC} = 1^{-+}$ exotic state with a mass of $1593 \pm 8^{+29}_{-47}$ MeV and a width of $168 \pm 20^{+150}_{-12}$ MeV [4] in the $\rho\pi$ channel in the reaction $\pi^- p \to \pi^+\pi^-\pi^- p$ at 18 GeV.

We have calculated the binding energy and decay modes of heavy hybrid mesons with a heavy quark in the framework of heavy quark effective theory using the light cone QCD sum rule technique [5]. In this work we extend the same formalism to calculate the decay widths of the processes $1^{-+} \to \rho\pi, f_1\pi, \pi\gamma$.

Denote the isovector $J^{PC} = 1^{-+}$ hybrid meson by $\tilde{\rho}$. The interpolating current for $\tilde{\rho}$ reads

$$J_\mu(x) = \bar{u}(x) g_s \gamma^\nu G^a_{\mu\nu}(x) \frac{\lambda^a}{2} d(x) \ , \tag{1}$$

The overlapping amplitude $f_{\tilde{\rho}}$ is defined as

$$\langle 0 | J_\mu(0) | \tilde{\rho} \rangle = \sqrt{2} f_{\tilde{\rho}} m^3_{\tilde{\rho}} \epsilon_\mu \ , \tag{2}$$

where ϵ_μ is the $\tilde{\rho}$ polarization vectors.

The decay amplitude for the p-wave decay process $\tilde{\rho} \to \rho\pi$ is

$$M(\tilde{\rho} \to \rho\pi) = i\epsilon_{\mu\alpha\sigma\beta}\epsilon^{\mu}e^{\alpha}q^{\sigma}p^{\beta}g_1 \ , \tag{3}$$

where e_μ is the polarization vector of the rho meson.

For the decay $\tilde{\rho} \to f_1(1285)\pi$, there exist two independent coupling constants, corresponding to S-wave and D-wave decays. Since the D-wave decay width is much smaller than S-wave width, we shall consider only the sum rules for the S-wave decay coupling constant. The decay amplitude is:

$$M(\tilde{\rho} \to f_1\pi) = (\eta \cdot \epsilon)g_2 + \cdots \ , \tag{4}$$

where η_μ is the polarization vector of f_1 meson.

We consider the correlators

$$i\int d^4x\ e^{ip\cdot x}\langle\pi(q)|T\left(J_\rho^\alpha(x)J_\mu^\dagger(0)\right)|0\rangle = i\epsilon_{\mu\alpha\sigma\beta}q^\sigma p^\beta G_1(p^2, p'^2) \ , \tag{5}$$

$$i\int d^4x\ e^{ip\cdot x}\langle\pi(q)|T\left(J_{f_1}^\alpha(x)J^{\dagger\mu}(0)\right)|0\rangle = g^{\mu\alpha}G_2(p^2, p'^2) + \cdots \ , \tag{6}$$

where $p' = p - q$, $J_\rho^\alpha(x) = \frac{1}{\sqrt{2}}[\bar{u}\gamma^\alpha u(x) - \bar{d}\gamma^\alpha d(x)]$, $J_{f_1}^\alpha(x) = \frac{1}{\sqrt{2}}[\bar{u}\gamma^\alpha\gamma_5 u(x) + \bar{d}\gamma^\alpha\gamma_5 d(x)]$, $< 0|J_\rho^\alpha|\rho >= f_\rho e^\alpha$, and $< 0|J_{f_1}^\alpha|f_1 >= f_{f_1}\eta^\alpha$.

Since the steps to derive the sum rule for the coupling constant $g_{1,2}$ are very similar to those in [5], we omit the details and present the final results directly.

$$\sqrt{2}f_{\tilde{\rho}}m_{\tilde{\rho}}^3 f_\rho m_\rho g_1 e^{-(\frac{m_\rho^2}{M_1^2}+\frac{m_{\tilde{\rho}}^2}{M_2^2})} = -\sqrt{2}f_\pi\{[\Phi_\perp(u_0)-\tilde{\Phi}_\perp(u_0)+\tilde{\Phi}_\parallel(u_0)]M^2+\frac{1}{36} < 0|g_s^2G^2|0 > \phi_\pi(u_0)\} \ , \tag{7}$$

$$\sqrt{2}f_{\tilde{\rho}}m_{\tilde{\rho}}^3 f_{f_1} m_{f_1} g_2 e^{-(\frac{m_{f_1}^2}{M_1^2}+\frac{m_{\tilde{\rho}}^2}{M_2^2})} = \frac{f_\pi}{\sqrt{2}}\{[\Phi'_\perp(u_0)-2\tilde{\Phi}'_\perp(u_0)]M^4+\frac{1}{36} < 0|g_s^2G^2|0 > \phi'_\pi(u_0)M^2\} \ , \tag{8}$$

where $u_0 = \frac{M_1^2}{M_1^2+M_2^2}$, $M^2 \equiv \frac{M_1^2 M_2^2}{M_1^2+M_2^2}$, M_1^2, M_2^2 are the Borel parameters. The definitions of pion wave functions can be found in [5, 6] and $\Phi'_\perp(u) = \frac{d\Phi_\perp(u)}{du}$ etc. The sum rule is asymmetric with the Borel parameter M_1^2 and M_2^2 since the hybrid meson is heavier than the rho or $f_1(1285)$ meson. For simplicity, we have given the expressions after integration of the double spectral density in the interval $(0, \infty)$ for the right hand side of (7) and (8). The subtraction of the continuum contribution is discussed in [5], which is crucial for the numerical analysis.

The values of the input parameters are $f_\pi = 0.132$ GeV, $m_{\tilde{\rho}} = 1.6$ GeV, $f_{\tilde{\rho}} = 0.026$ GeV [7], $m_\rho = 0.77$ GeV, $f_\rho = 0.22$ GeV, $m_{f_1} = 1.285$ GeV, $f_{f_1} = 0.24$ GeV. We have used the mass sum rules of $f_1(1285)$ [8] to obtain f_{f_1}. Moreover we use $\delta = 0.18$ GeV^2 instead of $\delta = 0.2$ GeV^2 as in [5, 6].

Let $M_1^2 = 2\beta m_{\rho,f_1}^2$, $M_2^2 = 2\beta m_{\tilde{\rho}}^2$, where β is the dimensionless scale parameter. Then we have $u_0 = \frac{m_{\rho,f_1}^2}{m_{\rho,f_1}^2+m_{\tilde{\rho}}^2}$, $M^2 = \frac{2m_{\rho,f_1}^2 m_{\tilde{\rho}}^2}{m_{\tilde{\rho}}^2+m_{\rho,f_1}^2}\beta$.

The sum rules (7) and (8) is stable with reasonable variation of the Borel parameter M^2 and the continuum threshold s_0. In order to avoid the possible contamination from the radial excited states $\rho(1450)$ and $f_1(1420)$ we choose the continuum $s_0 = (2.2 \pm 0.2)$GeV^2. Numerically we have

$$g_1 = (2.6 \pm 1.2)\text{GeV}^{-1} \ , \tag{9}$$

$$g_2 = (5 \pm 2)\mathrm{GeV}\ . \tag{10}$$

The central value corresponds to $\beta = 1.2$ and $s_0 = 2.2$ GeV^2. The errors refers to the variations with M^2, uncertainty of s_0, uncertainty of the pion wave functions, and the inherent uncertainty of the light cone qCD sum rule approach. Especially the sum rule for g_2 involves the first derivative of pion wave functions so it is less reliable than that for g_1.

The coupling constant $|g_1|$ was first calculated to be around $2 \sim 7$ GeV^{-1} with $m_{\tilde{\rho}} = 1.3$ GeV using three-point correlation functions at the symmetric point $p^2 = q^2 = p'^2$ in [9]. Later the hybrid mass and vertex sum rules were reanalysed leading to $g_1 = 9 \sim 10$ GeV^{-1} [10] and 7.7 GeV^{-1} [7] with $m_{\tilde{\rho}} = 1.5$ GeV. The sum rules calculated at the symmetric point receive large contamination from the higher resonances and the continuum contribution since only single Borel transformation can be invoked, which renders its prediction less relaible. In order to illustrate this point more clearly we let $s_0 \to \infty$, i.e., with the continuum contribution unsubtracted. In this case we arrive at $g_1 = (5.2 \pm 2.0)$ GeV^{-1}, which is numerically close to the value $g_1 = 7.7$ GeV^{-1} in [7]. In other words, the continuum contributes as large as the ground state so its subtraction is cruicial for a reliable extraction of the coupling constant.

The formulas of the decay widths are

$$\Gamma(\tilde{\rho}^- \to \rho^-\pi^0 + \rho^0\pi^-) = \frac{g_1^2}{12\pi}|\vec{q}_\pi|^3\ , \tag{11}$$

$$\Gamma(\tilde{\rho}^- \to f_1\pi^-) = \frac{g_2^2}{24\pi}\frac{|\vec{q}_\pi|}{m_{\tilde{\rho}}^2}(3 + \frac{|\vec{q}_\pi|^2}{m_{f_1}^2})\ , \tag{12}$$

where $|\vec{q}_\pi|$ is the pion decay momentum. Numerically,

$$\Gamma(\tilde{\rho} \to \rho\pi) = (40 \pm 20)\mathrm{MeV}\ , \tag{13}$$

$$\Gamma(\tilde{\rho} \to f_1\pi) = (100 \pm 50)\mathrm{MeV}\ . \tag{14}$$

We may further assume the vector dominance to relate the coupling constant for the process $\tilde{\rho} \to \gamma\pi$ to g_1 as in [10], $g_{\tilde{\rho}\gamma\pi} = \frac{e}{2\gamma_\rho}g_1 \sim 0.15$ GeV^{-1}, where $\gamma_\rho = 2.56$. In this way we can estimate $\Gamma(\tilde{\rho} \to \gamma\pi) \approx g^2_{\tilde{\rho}\gamma\pi}\frac{m^3_{\tilde{\rho}}}{96\pi} \sim 300$ keV. The width of $\rho\pi$ decay channel from the present calculation is much smaller than those from the vertex sum rules, which is 600 MeV [10] and 250 MeV [7].

One might take a step further and try to extend the same formalism to the decay process $1^{-+} \to b_1(1235)\pi$. However, the $b_1(1235)$ mass sum rule is not stable [8]. We do not consider this mode in this work. In short summary we have updated the QCD sum rule predictions for the pionic coupling constants in the light exotic meson decays and estimated the widths of some decay modes.

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